Chapter 4. Research and Analysis

"What is now proved was once only imagin'd"
—William Blake

"The purpose of models is not to fit the data but to sharpen the questions."
—Samuel Karlin

Theory

The NAS decadal survey *Astronomy and Astrophysics in the New Millennium* recognized theoretical studies as a central component of modern mission technology development. Theoretical studies include conceptual and analytical theory, development of software technologies supporting data exploration, astrophysical simulations, and combinations of these. That survey recommended that support for theory be explicitly funded as part of each mission funding line, because detailed modeling connecting the elements of a mission to the system under investigation is critical to design and even to conceive successful and cost-effective missions. Rigorous modeling is an important factor in reducing mission risk and evaluating competing mission strategies, and simulations can vividly demonstrate mission goals. *Beyond Einstein* explores to the boundaries of foundational knowledge as well as to the boundaries of spacetime, so detailed and quantitative theoretical studies are indispensable, starting with the earliest design phases.

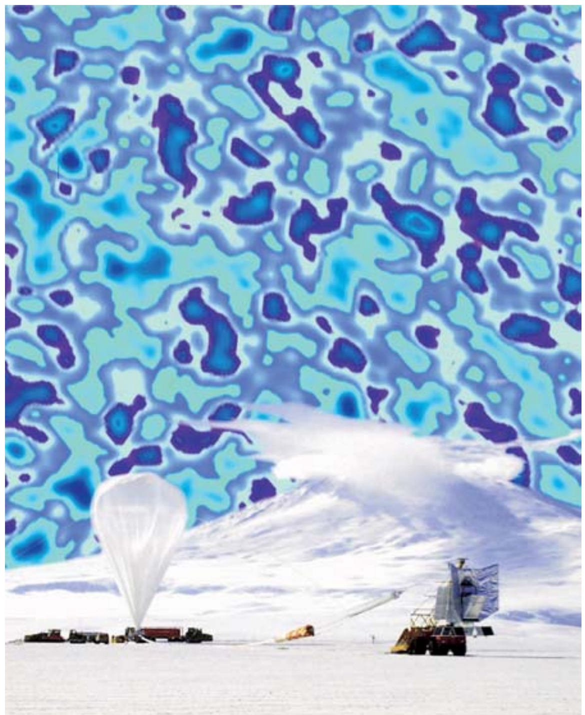
Some examples of necessary theoretical studies supporting *Beyond Einstein* are:

- Constellation-X. Models of relativistic hydrodynamic flows in accretion disks, including radiative transfer models, leading to simulated, time-dependent spectra.
- LISA. Studies and simulations of signal extraction in the presence of multiple, overlapping signals; numerical relativity, aimed at accurate calculation of predicted gravitational waveforms for the whole range of merging and orbiting systems; astrophysical modeling and simulations to connect binary population predictions with other data sets.
- Inflation Probe. Theoretical studies of early Universe cosmology, including tensor and scalar mode predictions and their connection with fundamental theory; simulations of polarization effects, including the contamination effects of astrophysical foregrounds and gravitational lensing; development of optimal statistical signal extraction techniques.
- Dark Energy Probe. Theoretical studies of Type Ia supernovae and other candidate systems for calibrating cosmic distances, including simulations of statistical effects of gravitational lensing by dark matter; realistic simulation of various competing techniques (e.g., galaxy clusters, quasar clustering) to facilitate evaluation of most precise and reliable methods. Theoretical work combining anticipated new results from particle theory and experiment with cosmology will be important to optimize the probe to test theories of dark energy.
- Big Bang Observer. Early Universe cosmology and phenomenology of quantum gravity, string theory, and brane world models; models of coalescing white dwarf and neutron star binaries and populations in the 0.1 to 1 Hz range.
- Black Hole Imager. Comprehensive simulation of black hole environments, including electromagnetic field interactions with flows and the spacetime metric, and radiative transfer over many decades of dynamic range.

Supporting Ground-Based Research and Analysis

Beyond Einstein missions also require specialized supporting ground-based programs. As in the case of theory, these studies should start early in the program since they will influence the optimization of the mission design parameters. In the case of the Einstein Probes, a broad effort is needed since even the mission concept will be competed.

The Inflation Probe, if it is based on microwave background anisotropy polarization, will require new generations of polarization-sensitive detectors, excellent control of systematic effects, and a thorough understanding of astrophysical foregrounds. Ground-based cosmic microwave background polarization experiments will be essential preparation for the Inflation Probe, both for testing of new technology, investigation of observing strategies and systematics, and for providing data to test new analysis techniques. Detector technology for COBE, WMAP, and Planck was a direct product of ground-based and sub-orbital programs. In the same way, a strong ground-based program is an essential precursor to the Inflation Probe.



The BOOMERanG measurements performed under the supporting research and analysis program were obtained from suborbital balloon flights and provided key measurements on the shape of the Universe from observations of the cosmic microwave background.

Whatever technique is adopted, the Dark Energy Probe will require ground-based data of unusual uniformity, quality, and completeness. If Type Ia supernovae are employed, space studies must be supported by detailed and precise ground-based spectra and photometry of a large, uniformly selected sample of relatively nearby supernovae. This is required both as a calibrating set for the high-redshift Hubble diagram and as a statistical control sample to study the systematic correlations of supernova properties—the generalization of the one-parameter fits to light curve shape currently being used. Similar foundational studies are needed for other candidate techniques for the Dark Energy Probe. Programs supporting ground-based studies of this type are already underway with funding from the National Science Foundation and the Department of Energy.